CHAPTER 13
AXIAL-FLOW TURBINES

Axial-flow turbines are used in most applications involving compressible fluids.[1] They power most gas turbines except the smaller ones. Their efficiency is higher than radial-inflow turbines in most operating ranges. Axial-flow turbines are also used in steam turbine applications. However, there are significant differences between the design of axial-flow turbines used in gas turbines and those used in steam turbine applications.

There are *impulse* and *reaction-type* steam turbines. Most reaction-type steam turbines have a 50 percent reaction level. This design has proven to be very efficient. The reaction level varies considerably in the blades of gas turbines. Axial-flow turbines used today have a high work factor (ratio of stage work to square of blade speed). This is done to achieve lower fuel consumption and to reduce noise from the turbine.

TURBINE GEOMETRY

The important state points used to analyze the flow within a turbine are indicated at the following locations in Fig. 13.1:

0—The nozzle entrance

1—The rotor entrance

2—The rotor exit

The fluid velocity is an important parameter for analyzing the flow and energy transfer within a turbine. The fluid velocity relative to a stationary point is called the *absolute velocity,* **V.** This is an important term for analyzing the flow across a stationary blade such as a nozzle.* In turbine applications, the stationary blades of the turbine are called *nozzles.*

The relative velocity, **W,** is used when analyzing the flow across a rotating element such as a rotor blade. It is defined as:

$$\mathbf{W} = \mathbf{V} - \mathbf{U} \tag{13.1}$$

where **U** is the tangential velocity of the blade. Figure 13.2 illustrates this relationship. Subscripts z and o denote the axial and tangential component of velocity, respectively.

*A nozzle is defined as a channel of decreasing cross-sectional area.

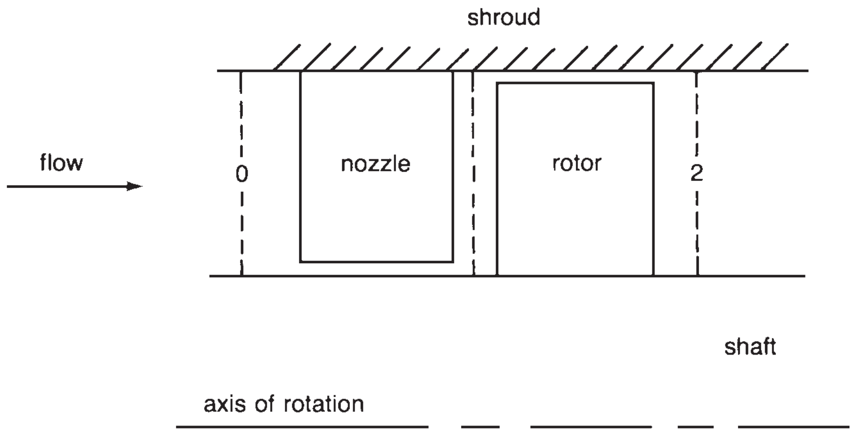


FIGURE 13.1 Axial turbine flow.

Degree of Reaction

The *degree of reaction* in an axial flow turbine having a constant axial velocity and a rotor with a constant radius is given by:

$$R = \frac{(W_4^2 - W_3^2)}{(V_3^2 - V_4^2) + (W_4^2 - W_3^2)} \tag{13.2}$$

For an impulse turbine (zero reaction), the relative exit velocity W_4, must be equal to the relative inlet velocity W_3. The degree of reaction of most turbines is between 0 and 1. Negative reaction turbines are not normally used due to their lower efficiencies.

Utilization Factor

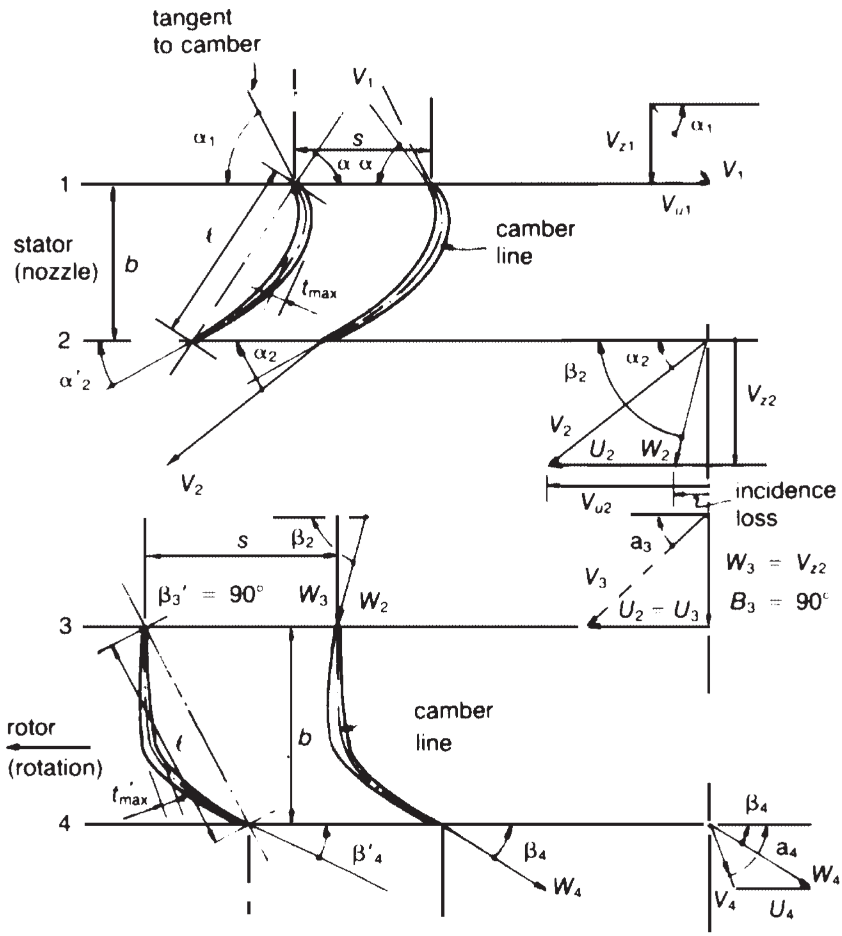
The turbine cannot convert all of the energy supplied into useful work. There is some energy discharged due to the exit velocity. The *utilization factor* is defined as the ratio of ideal work to the energy supplied. For a turbine having a single rotor with constant radius, the utilization factor is given by:

$$E = \frac{(V_3^2 - V_4^2) + (W_4^2 - W_3^2)}{V_3^2 + (W_4^2 - W_3^2)} \tag{13.3}$$

Work Factor

The *work factor* is used to determine the blade loading. It is given by the following expression for a turbine having a constant radius:

$$\Gamma = \frac{V_{\phi 3} - V_{\phi 4}}{U} \tag{13.4}$$



Stator: incidence $t_s = \alpha_1 - \alpha_1'$ $\quad t_s > 0$ when $\alpha_1 > \alpha_1'$
deviation $\sigma_s = \alpha_2' - \alpha_2$
deflection $t_s = \alpha_1 + \alpha_2$ $\quad$ camber $\theta_s = \alpha_1' + \alpha_2'$
Rotor: incidence $t_r = \beta_2 - \beta_3'$ $\quad t_r > 0$ when $\beta_2 > \beta_3'$
deviation $\sigma_r = \beta_4' - \beta_4$
deflection $t_r = \beta_2 - \beta_4$ $\quad$ camber $\theta_r = \beta_3' + \beta_4'$

FIGURE 13.2 Stage nomenclature and velocity triangles.

For an impulse turbine (zero reaction) with a maximum utilization factor, the value of the work factor is 2. The value of the work factor for a 50 percent reaction turbine with a maximum utilization factor is 1.

Modern turbines have a high work factor. This indicates that the blade loading of the turbine is high. The efficiency of the turbine tends to decrease as the work factor increases.

IMPULSE TURBINE

The impulse turbine has the simplest design. The gas is expanded in the nozzles (stationary blades). The high thermal energy (high temperature and pressure) is converted into kinetic energy. This conversion is given by the following relationship:

$$V_3 = \sqrt{2\Delta h_0} \tag{13.5}$$

where V_3 is the absolute velocity of the gas entering the rotor and Δh_0 is the change of enthalpy across the nozzles.

The high-velocity gas impinges on the rotating blades. Most of the kinetic energy in the gas stream will be converted to turbine shaft work. Figure 13.3 illustrates the velocity and pressure distribution in a single-stage impulse turbine. The absolute velocity of the gas increases in the nozzle due to the decrease in static pressure and temperature. The absolute velocity is then decreased across the rotating blades. However, the static pressure and the relative velocity remain constant. The maximum energy is transferred to the blades when they rotate at around one-half the velocity of the gas jet. Most turbines have two or more rows of moving blades for each nozzle. This is done to obtain low stresses and low speed at the tip of the blades. Guide vanes are installed in between the rows of the moving blades to redirect the gas from one row of moving blades to another (see Fig. 13.4). This type of turbine is known as the *Curtis* turbine.

The *pressure compound* or *Ratteau turbine* is another type of impulse turbine. In this design, the work is broken down into stages. Each stage consists of a row of nozzles and a row of moving blades. The kinetic energy in the jet leaving the nozzles is converted into useful work in the turbine rotor. The gas leaving the moving blades enters the nozzles of the next stage where the enthalpy decreases further and the velocity increases. The kinetic

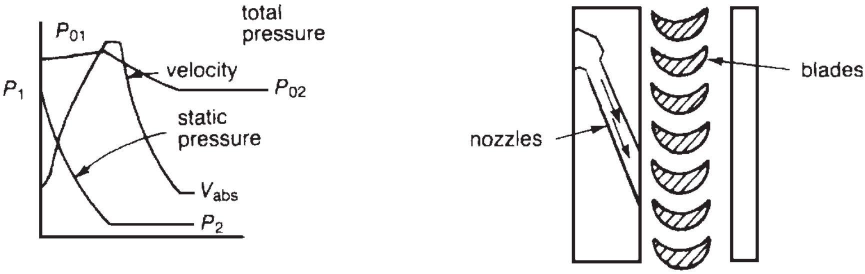


FIGURE 13.3 View of a single-stage impulse turbine with velocity and pressure distribution.

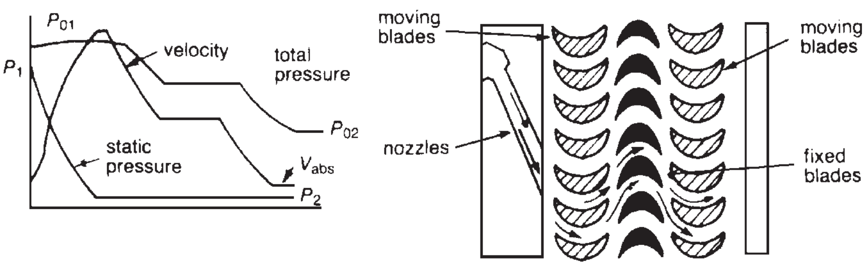


FIGURE 13.4 Pressure and velocity distributions in a Curtis-type impulse turbine.

energy of the gas leaving the nozzles of this stage is converted by the associated row of moving blades. Figure 13.5 illustrates a Ratteau turbine.

The degree of reaction in an impulse turbine is equal to zero. This indicates that the entire enthalpy drop of a stage is taken across the nozzles, and the velocity leaving the nozzles is very high. Since there is no change of enthalpy across the moving blades, the relative velocity entering them equals the relative velocity at the exit.

THE REACTION TURBINE

The axial-flow reaction turbine is the most common one throughout industry. The nozzles and moving blades of this turbine act as expanding nozzles. Therefore, the enthalpy (pressure and temperature) decreases in both the fixed and moving blades. The nozzles direct the flow to the moving blades at a slightly higher velocity than the moving blades. The velocities in a reaction turbine are normally much lower than the impulse turbine, and the relative velocities entering the blades are almost axial. Figure 13.6 illustrates a view of a reaction turbine.

Reaction turbines usually have a higher efficiency than impulse turbines. However, the amount of work generated by impulse turbines is higher than reaction turbines. Therefore, most modern multistage turbines have the impulse design in the first few stages to maximize the pressure drop while the remaining stages are 50 percent reaction. This combination has proven to be an excellent compromise.

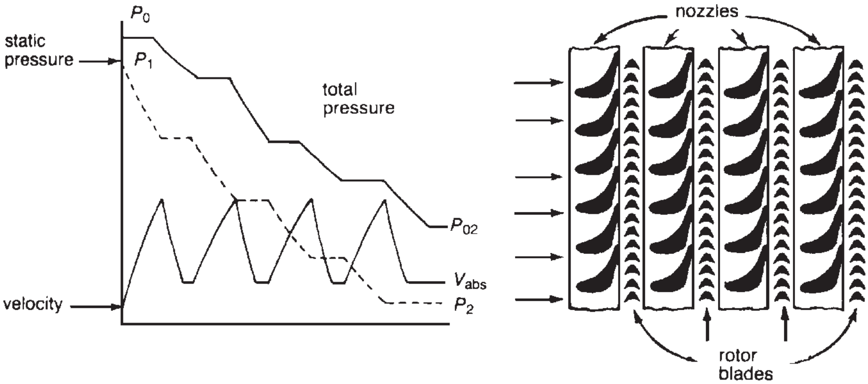


FIGURE 13.5 Pressure and velocity distributions in a Ratteau-type impulse turbine.

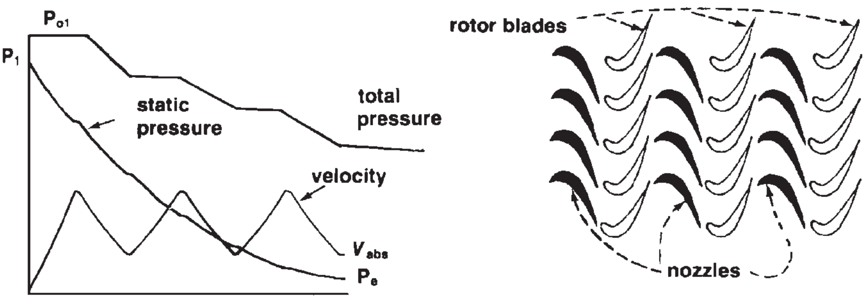


FIGURE 13.6 Velocity and pressure distribution in a three-stage reaction turbine.

TURBINE BLADE COOLING METHODS

During the last few decades, the turbine inlet temperatures of gas turbines have increased from 1500°F (815°C) to around 2500°F (1371°C). This trend will continue due to the increase in specific power and efficiency associated with the increase in turbine inlet temperature. This increase in temperature has been made possible by advancements in metallurgy and the use of advanced cooling techniques for the turbine blades. The cooling air is taken from the compressor discharge and directed to the rotor, stator, and other parts of the machine to provide adequate cooling. Figure 13.7 illustrates the five basic methods used for cooling in gas turbines:

1. Convection cooling
2. Impingement cooling
3. Film cooling
4. Transpiration cooling
5. Water cooling

Convection Cooling

Convection cooling is achieved by having the flow of cooling air inside the turbine blade to remove heat across the wall. The airflow is normally radial. It makes multiple passes through a serpentine channel from the hub to the tip of the blade. Convection cooling is the most common technique used in gas turbines.

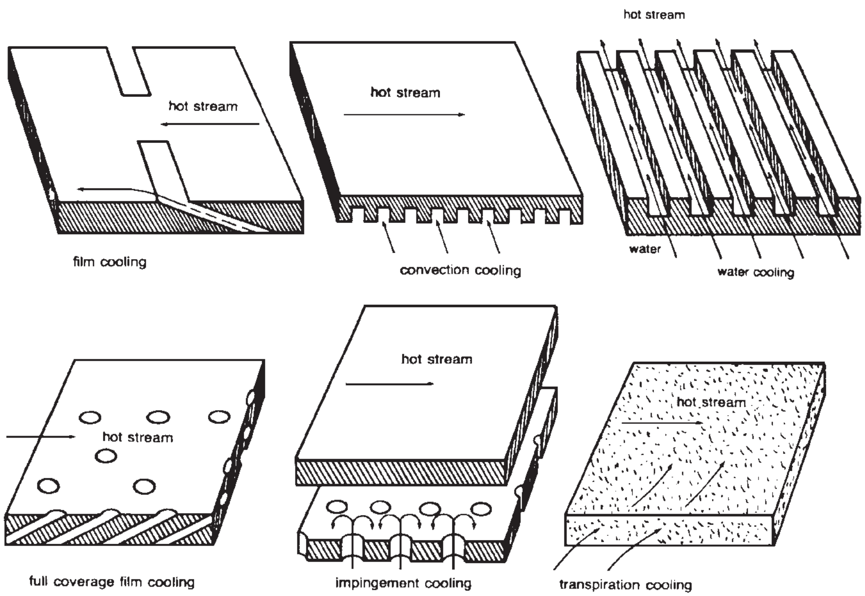


FIGURE 13.7 Various suggested cooling schemes.

Impingement Cooling

Impingement cooling is a form of convection cooling where the cooling air is blasted on the inner surface of the airfoil by high-velocity air jets. This increases the heat transfer from the metal surface to the cooling air. This technique can be limited to desired sections of the airfoil to maintain even temperatures over the entire surface. For example, the leading edge of the blade requires more cooling than the midchord section or trailing edge. Thus, the cooling air is impinged at the leading edge to enhance the cooling in this section.

Film Cooling

Film cooling is achieved by allowing the cooling air to establish an insulating layer between the hot gas stream and the blade. This technique is also used to protect the combustor liners from the hot gases.

Transpiration Cooling

Transpiration cooling is achieved by passing the cooling air through the porous wall of the blade. The air cools the hot gases directly. This method is effective at very high temperatures because the entire blade is covered with coolant flow.

Water Cooling

Water cooling involves passing water through tubes embedded in the blade. The water is then discharged from the tip of the blade as steam. The water must be preheated before entering the blade to prevent thermal shock. This method lowers the blade temperature below 1000°F (538°C).

TURBINE BLADE COOLING DESIGNS

The following are five different blade-cooling designs:

1. *Convection and Impingement Cooling/Strut Insert Design.* Figure 13.8 illustrates a strut insert design. Convection cooling is applied to the midchord section through horizontal fins, and impingement cooling is applied to the leading edge. The coolant exits through a split trailing edge. The air flows upward in the central cavity formed by the strut insert and through holes at the leading edge of the insert to cool the leading edge of the blade by impingement. The air then enters through horizontal fins between the shell and strut and discharges through slots at the trailing edge of the blade. Figure 13.9 illustrates the temperature distribution for this design.
2. *Film and Convection Cooling Design.* Figure 13.10 illustrates this blade cooling design. The midchord region is cooled by convection and the leading edges by convection and film cooling. The cooling air is injected through three ports from the base of the blade. It circulates up and down through a series of vertical channels and then passes through a series of small holes at the leading edge. It impinges on the inside surface of the leading edge and passes through holes to provide film cooling. The air discharging through slots cool the trailing edge by convection. Fig. 13.11 illustrates the temperature distribution for this design.

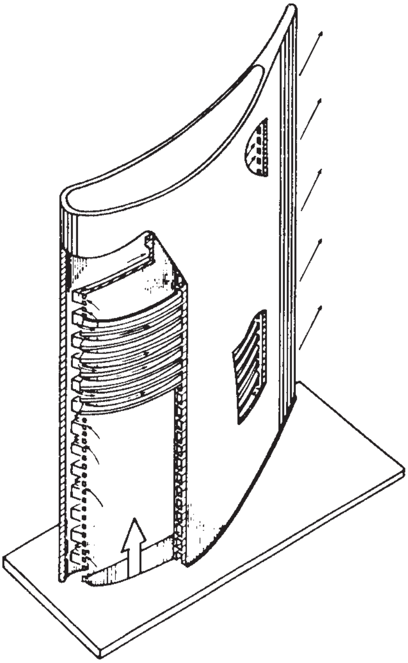


FIGURE 13.8 Strut insert blade.

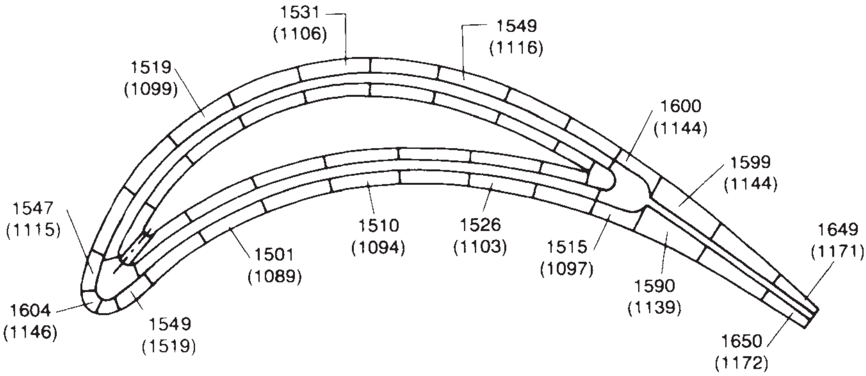


FIGURE 13.9 Temperature distribution for strut insert design, °F (cooled).

3. *Transpiration Cooling Design.* The blades cooled by this method have a strut-supported porous shell (see Fig. 13.12). The cooling air enters the blade through the central plenum of the strut, which has different-size metered holes on its surface. The air passes through the porous shell that is cooled by a combination of convection and film cooling. This technique is effective due to the infinite number of pores in the shell. Figure 13.13 illustrates the temperature distribution. Oxidation closes some of the pores during normal operation, causing uneven cooling and high thermal stresses. Thus, there is a higher probability of blade failure when this design is used.

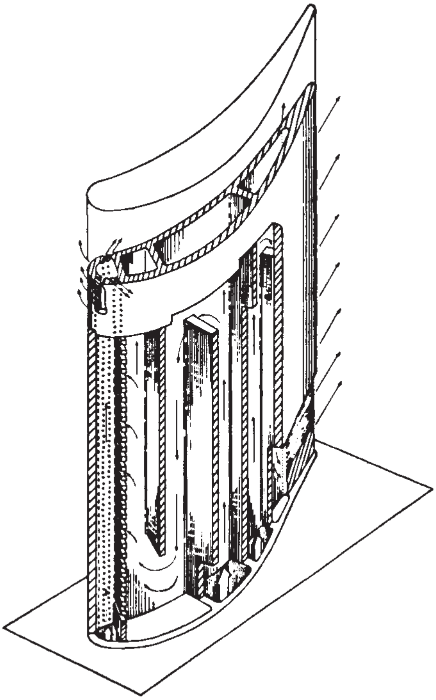


FIGURE 13.10 Film and convection-cooled blade.

4. *Multiple Small-Hole Design.* In this design, cooling air is injected through small holes over the airfoil surface (Fig. 13.14). The cooling is mainly achieved by film-cooling. Figure 13.15 illustrates the temperature distribution. These holes are much larger than the ones used for transpiration cooling. Thus, they are less susceptible to clogging by oxidation. Cross-ribs are used in this design to support the shell. This technique is considered to be among the best in modern gas turbines.

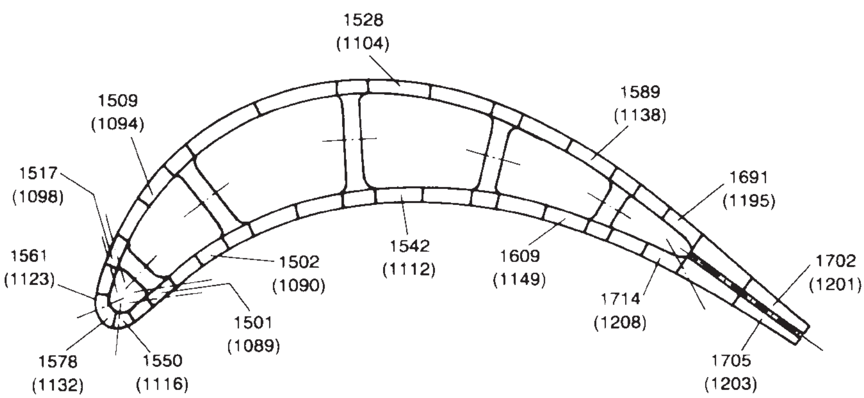


FIGURE 13.11 Temperature distribution for film convection-cooled design, °F (cooled).

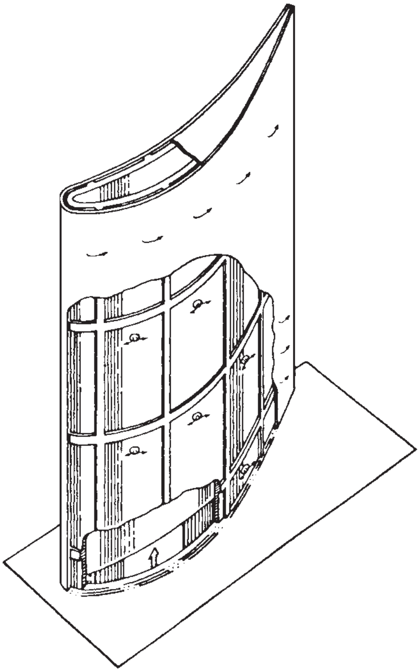


FIGURE 13.12 Transpiration-cooled blade.

5. *Water-Cooled Turbine Blades.* This technique has a number of water tubes embedded inside the blade (Fig. 13.16). The tubes are normally made of copper to provide good heat transfer. The water must be preheated before entering the blade to prevent thermal shock. It evaporates when it reaches the tip of the blade. The steam is then injected into the flow stream. This design is very promising for future gas turbines where the turbine inlet temperature is expected to be around 3000°F (1649°C). This technique will keep the blade temperature below 1000°F (538°C). Thus, there will be no problems with hot-corrosion.

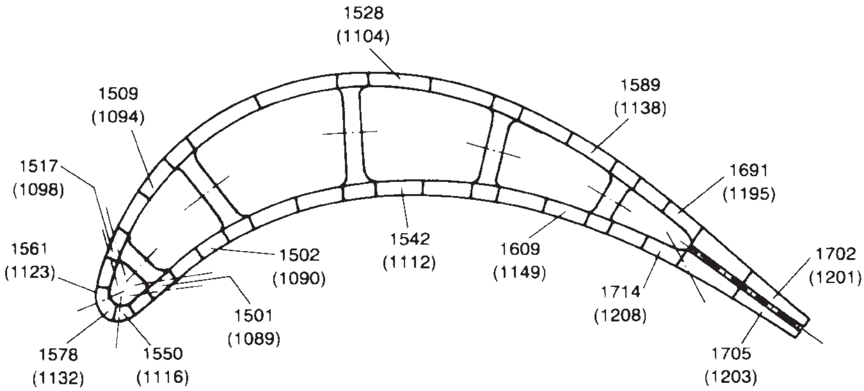


FIGURE 13.13 Temperature distribution for film transpiration-cooled design, °F (cooled).

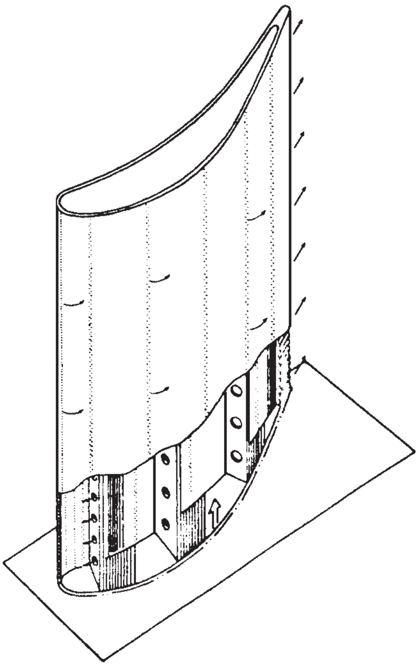


FIGURE 13.14 Multiple small-hole transpiration-cooled blade.

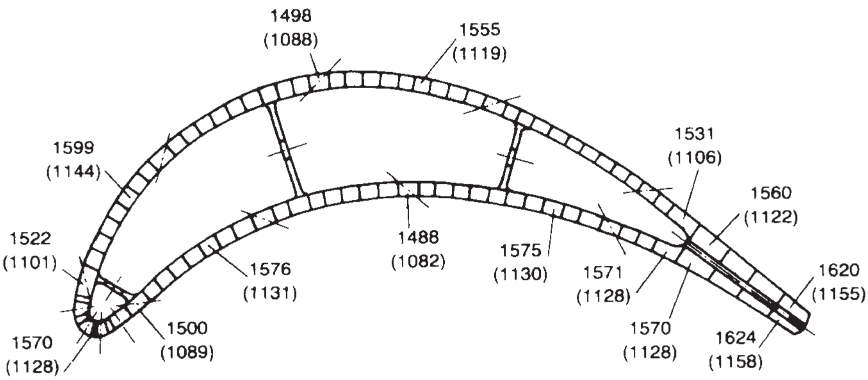


FIGURE 13.15 Temperature distribution for a multiple small-hole design, °F (cooled).

COOLED-TURBINE AERODYNAMICS

The efficiency of the turbine decreases when cooling air is injected into the rotor or stator (Fig. 13.17). However, the injection of cooling air into the turbine allows higher temperature in the combustors. This results in increase in the overall efficiency of the gas turbine.

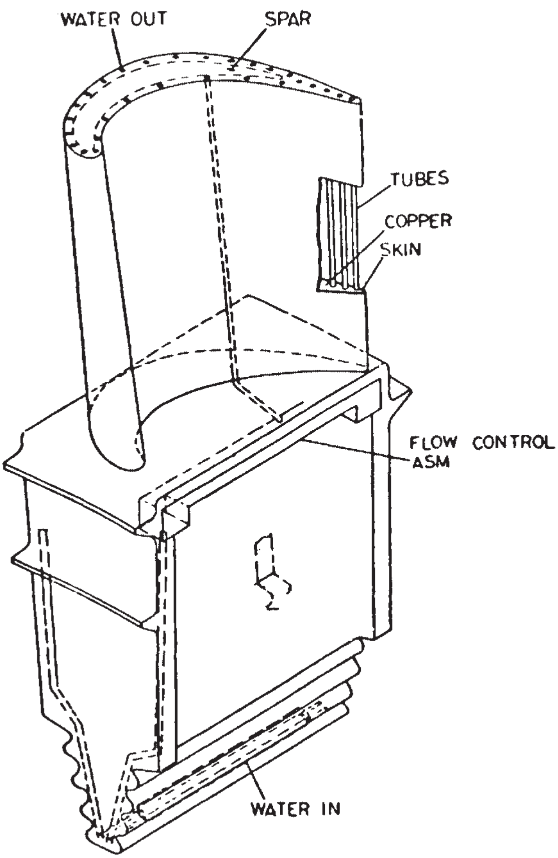


FIGURE 13.16 Water-cooled turbine blade. (*Courtesy General Electric Company*)

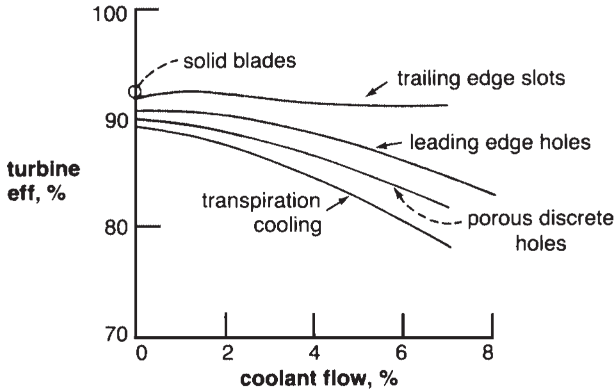


FIGURE 13.17 The effect of various types of cooling on turbine efficiency.

REFERENCE

Boyce, Meheran P., *Gas Turbine Engineering Handbook,* Gulf Publishing Company, Houston, Tex., © 1982, reprinted July 1995.